FTUV/99-13
IFIC/99-13
UWThPh-1999-12
FSU-HEP-030399

R-parity violating decays of the Top-Quark and the Top-Squark at the Tevatron[a]

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Abstract. We study unconventional decays of the top-quark and the top-squark in the framework of SUSY models with broken R-parity. The model under study is the MSSM with an additional bilinear term that breaks R-parity. In this model the top-squark behaves similar to a third generation leptoquark. We demonstrate that existing Tevatron data on the top give rise to restrictions on the SUSY parameter space. In particular, we focus on scenarios where the tau-neutrino mass is smaller than 1 eV. We give an exclusion plot derived from the leptoquark searches at Tevatron.

I INTRODUCTION

The search for supersymmetry (SUSY) is one of the main tasks in the experimental program of the Tevatron. Most of the studies have been carried out in the framework of the Minimal Supersymmetric Standard Model (MSSM) (see e.g. [1] and references therein). There has also been considerable work in the case of R-parity violation [2] (for collider studies see e.g. [3] and references therein). The latter ones have mainly treated the case of trilinear R-parity violating couplings (TRPV). Here we focus on the case of bilinear R–Parity Violation (BRPV) [4–7] which contain as additional feature a vev for the sneutrinos. These models are well-motivated theoretically as they arise as effective truncations of models where R–Parity is broken spontaneously [8] through right handed sneutrino vacuum expectation values (vev) $\langle\tilde{\nu}^c\rangle = v_R \neq 0$. They open new possibilities for the study of the unification of the Yukawa couplings [9]. In particular it has been shown that in BRPV models bottom-tau unification may be achieved at any value of $\tan\beta$. From a phenomenological point of view these models predict a plethora of novel processes [10] that could reveal the existence of SUSY in a totally different way, not only through the usual missing momentum signature as predicted by the MSSM. They provide a very predictive approach to the violation of R–Parity, which renders the systematic study of R-parity violating physics [10] possible. Moreover, they are more restrictive than TRPV models, especially in their supergravity formulation, if universality of the soft-breaking terms is assumed at the unification scale, as in [4].

We will consider the simplest superpotential which violates R-Parity

$$W_{\not R_p} = W_{MSSM} + \epsilon_i \widehat{L}_i \widehat{H}_u \,, \tag{1}$$

assuming that TRPV terms are absent or suppressed, as would be the case if their origin is gravitational [11]. The ϵ_i terms violate lepton number in the ith generation respectively. As already mentioned, models where

[a] To appear in the proceedings of the workshop "Physics at Run II: Supersymmetry/Higgs Fermilab, Feb.–Nov. 1998"

R–Parity is broken spontaneously [8] through a vev of the right handed sneutrinos $\langle\tilde{\nu}^c\rangle = v_R \neq 0$ generate only BRPV terms. The ϵ_i parameters are then identified as a product of a Yukawa coupling and v_R. This provides the main theoretical motivation for introducing explicitly BRPV in the MSSM superpotential. For simplicity we set from now on $\epsilon_1 = \epsilon_2 = 0$, and in this way, only tau–lepton number is violated. In this case, considering only the third generation, the MSSM–BRPV has the following superpotential

$$W_{R_{\not p}} = \varepsilon_{ab}\left[h_t\widehat{Q}_3^a\widehat{U}_3\widehat{H}_u^b + h_b\widehat{Q}_3^b\widehat{D}_3\widehat{H}_d^a + h_\tau\widehat{L}_3^b\widehat{R}_3\widehat{H}_d^a + \mu\widehat{H}_u^a\widehat{H}_d^b + \epsilon_3\widehat{L}_3^a\widehat{H}_u^b\right], \qquad (2)$$

where the first four terms correspond to the MSSM. The last term violates tau–lepton number as well as R–Parity.

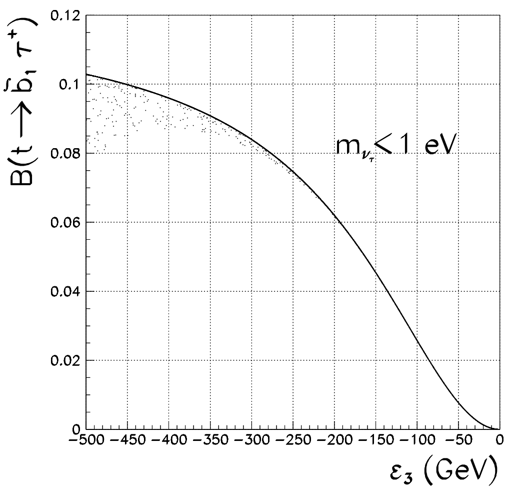

Fig. 1: Branching Ratios for $t \to \tilde{b}_1\tau^+$ as a function of ϵ_3. The parameters are: $M = 180$ GeV, $\mu = 200$ GeV, $\tan\beta = 35$, $M_{E_3} = 285$ GeV, $A_\tau = 280$ GeV, $M_Q = 285$ GeV, $M_U = 180$ GeV, $M_D = 190$ GeV, $A_t = 320$ GeV, $A_b = 120$ GeV, $B = 50$ GeV, -500 GeV $< \epsilon < 0$ GeV, 0 GeV $< B_2 < 200$ GeV, 1 GeV $< v_3 < 50$ GeV.

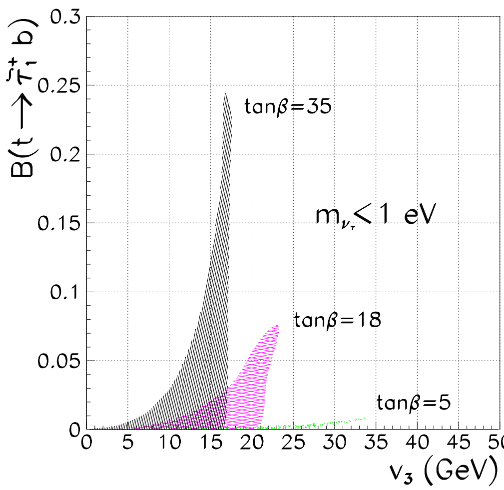

Fig. 2: Branching Ratios for $t \to \tilde{\tau}_1^+ b$ as a function of v_3 for different values of $\tan\beta$. The other parameters are the same as in Fig. 1.

It has often been claimed that the BRPV term can be rotated away from the superpotential by a suitable choice of the basis [12]. If this were true then the ϵ term would be unphysical. Indeed, one can show that, performing this rotation of the superfields one can indeed eliminate the BRPV but RPV is reintroduced in the form of TRPV. Moreover, supersymmetry must be broken and the presence of the ϵ term in the superpotential also introduces R-parity a violating term $\varepsilon_{ab}(B_2\epsilon_3 L_3^a H_u^b)$, in the scalar sector implying that the vacuum expectation value $\langle\tilde{\nu}_\tau\rangle = v_3/\sqrt{2}$ is non–zero. This in turn generates more R–parity and tau lepton number violating terms inducing a tau neutrino mass. Moreover, it is in general impossible to rotate away the bilinear term in the Superpotential and at the soft SUSY breaking potential at the same time.

In this model the top-quark as well as the top-squark get additional decay modes, e.g. $t \to \tilde{\tau}_1^+ b$ or $\tilde{t}_1 \to \tau^+ + b$. We study these decay in view of the Tevatron (top decays in TRPV models has been treated in [13]). We show that existing Tevatron data give additional constraints on the parameter space.

II TOP DECAYS

One of the major successes of Tevatron has been the discovery of the top-quark [14]. The large top mass implies a relatively small production cross section at the Tevatron. Therefore, the sum of all branching ratios of the top decays except $t \to W^+ b$ is only restricted to be smaller than approximately 25 % [15]. In the MSSM the top can decay according to: $t \to W^+ b$, $t \to H^+ b$, $t \to \tilde{\chi}_1^0\tilde{t}_1$, $t \to \tilde{\chi}_1^+\tilde{b}_1$. The last mode is only listed for completeness, because it is practically ruled out by existing LEP2–data [16]. In the BRPV model the charginos mix with the charged leptons, the neutralinos with neutrinos, and the charged sleptons with the charged Higgs boson [4–6]. Therefore, the top can have additional decay modes:

$$t \to \tilde{\tau}_1^+ \, b \,, \quad t \to \nu_\tau \, \tilde{t}_1 \,, \quad t \to \tau^+ \, \tilde{b}_1 \,. \tag{3}$$

As an illustrative example we show in Fig. 1 the branching ratio for $t \to \tau^+ \tilde{b}_1$ as a function of ϵ_3. We have randomly chosen 10000 points imposing the following constraints: $m_{\nu_\tau} < 18$ MeV, $m_{\tilde{t}_1}, m_{\tilde{b}_1} > 80$ GeV, $min(m_{H^+}, m_{\tilde{\tau}_1}) > 70$ GeV, and $m_{\tilde{\chi}_1^+} > 85$ GeV. The parameters are listed in the figure caption. We find a strong correlation between the R-parity decay branching ratio $BR(t \to \tau^+ \tilde{b}_1)$ and the magnitude of ϵ_3. This can be understood in the following way: in the chargino mass matrix the mixing between the leptons and the charginos disappears if one does the following rotation in the superfields: $\widehat{H}_1 \to N(\mu \widehat{H}_1 - \epsilon_3 \widehat{L}_3)$ and $\widehat{L}_3 \to N(\mu \widehat{L}_3 + \epsilon_3 \widehat{H}_1)$ (N being the normalization). In this basis the coupling between t, τ, and $\tilde{b}_1$ is proportional $N \, h_b \, \epsilon_3$ leading to this feature.

In Fig. 2 we show the branching ratio for $t \to \tilde{\tau}_1^+ b$ as a function of v_3. Results in Fig. 2 are displayed for different values of $\tan\beta$ and the other parameters are also the same as in Fig. 1 . The dependence on $\tan\beta$ is a result of: (i) The stau - charged Higgs boson mixing is proportional to the R-parity breaking parameters ϵ_3 and v_3 (ii) The decay width depends on the bottom Yukawa coupling which increases with $\tan\beta$. As can be seen from the figure there is a strong correlation between the magnitude of the R-parity breaking branching ratios and the mixing between the stau and the charged Higgs boson.

We have performed a similar scan for small $\tan\beta$ for both of BRPV decay channels discussed above. These are suppressed in this case and can not exceed 2% or so, i.e. $(\sum BR(t \to b \, X) < 1 - 2\% \, (X \neq W))$, because their decay widths are in all cases proportional to the bottom Yukawa coupling squared. In the case of $t \to \tau^+ \tilde{b}_1$ this is clear from the discussion of Fig. 1. In the case of $t \to \tilde{\tau}_1^+ b$ one has to note that the stau mixes mainly with charged component of the down-type Higgs multiplet H_1 ($\tilde{\tau}_L$ and H_1 have the same gauge quantum numbers) and the $H_1 tb$ coupling is proportional to h_b.

In every case the various decay modes lead to cascade decays:

$$\begin{array}{lll}
t \to \tilde{\tau}_1^+ \, b & \to \tau^+ \, \nu_\tau \, b & \\
 & \to \tau^+ \, \tilde{\chi}_1^0 \, b & \to \tau^+ \, f \, \bar{f} \, \nu_\tau \, b \\
 & & \to \tau^+ \, f \, \bar{f}' \, \tau^\pm \, b \\
 & \to \nu_\tau \, \tilde{\chi}_1^+ \, b & \to \nu_\tau \, f \, \bar{f}' \, \nu_\tau \, b \\
 & & \to \nu_\tau \, f \, \bar{f} \, \tau^+ \, b \\
 & \to c \, s \, b & \\
t \to \tau^+ \, \tilde{b}_1 & \to \tau^+ \, \nu_\tau \, b & \\
 & \to \tau^+ \, \tilde{\chi}_1^0 \, b & \to \tau^+ \, f \, \bar{f} \, \nu_\tau \, b \\
 & & \to \tau^+ \, f \, \bar{f}' \, \tau^\pm \, b
\end{array}$$

In nearly all cases there are two τ's and two b-quarks in the final state plus the possibility of additional leptons and/or jets. Therefore, b-tagging and a good τ identification are important for extracting these final states. Moreover there is in general a large multiplicity of charged particles in the final state which should be helpful in reducing the background. The background will come mainly from the production of one or two gauge bosons plus additional jets. The conclusion in similar cases [18] has been that in its next run the Tevatron should be sensitive to branching ratio values up to $10^{-3} - 10^{-2}$ depending on the mode. Therefore, the possible observation of one of these additional decay modes at the run 2 of Tevatron should give a strong hint on the underlying parameters.

III TOP-SQUARK DECAYS

Top-squark physics is a very interesting part of supersymmetric theories, because the lighter top-squark might be the lightest charged SUSY particle. This follows because: (i) The large top Yukawa coupling leads to reduced soft SUSY breaking masses compared to the first two generation in GUT models (see e.g. [19] and references therein), and (ii) The off-diagonal element of the top-squark mass matrix is proportional to the top mass leading to a strong mixing and possible light mass eigenstate.

In the kinematical reagion accessible to the Tevatron the light top-squark has the following MSSM decay modes: $\tilde{t}_1 \to \tilde{\chi}_i^+ + b$, $\tilde{t}_1 \to \tilde{\chi}_1^0 + c$, $\tilde{t}_1 \to \tilde{l}_i^+ + \nu_l + b$, $\tilde{t}_1 \to \tilde{\nu}_l + l^+ + b$, $\tilde{t}_1 \to \tilde{\chi}_1^0 + W^+ + b$, and $\tilde{t}_1 \to \tilde{\chi}_1^0 + H^+ + b$ (for a discussion see e.g. [20] and references therein). In BRPV models the top-squark has an additional and phenomenologically very interesting decay mode [21]:

$$\tilde{t}_1 \to \tau^+ + b \tag{4}$$

In the following we have concentrated on scenarios where only the two-body decay modes are possible. We adopt the framework of Supergravity unification [4] in order to reduce the number of free SUSY parameters. However, we keep ϵ_3 and v_3 as free parameters for the moment. In Fig. 3 we show the areas in the $m_{\tilde{t}_1}$-$m_{\tilde{\chi}_1^0}$ plane where the branching ratio $\tilde{t}_1 \to \tau^+ + b$ is larger than 90% for different values of ϵ_3 and v_3. We restrict to the range $|\epsilon_3|, |v_3| < 1$ GeV, and vary randomly the MSSM parameters keeping $m_{\tilde{t}_1} < m_{\tilde{\chi}_1^\pm} + m_b$. This

demonstrates that one can get a dominance of the R-Parity violating decay mode even for relatively small values of the R-parity breaking parameters. The upper–left triangular region corresponds to $m_{\tilde{t}_1} < m_{\tilde{\chi}^0_1} + m_c$ and thus $BR(\tilde{t}_1 \to b\tau) = 1$. In the lower–right triangular region $m_{\tilde{t}_1} > m_{\tilde{\chi}^+_1} + m_b$ and therefore $\tilde{t}_1 \to b\,\tilde{\chi}^+_1$ is open. In the central region the top-squark has the two decay modes $\tilde{t}_1 \to b\,\tau$ and $\tilde{t}_1 \to c\,\tilde{\chi}^0_1$. The solid lines, defined by the maximum value of $|\epsilon_3|$ and $|v_3|$, are the boundary of the regions where $BR(\tilde{t}_1 \to b\tau) > 0.9$ such that points at the left of the boundary satisfy that condition.

Since BRPV models allow the decay $(\tilde{t}_1 \to \tau^+ + b)$ we can interpret the top squark as a third generation leptoquark. Therefore we can use the limits obtained from leptoquark searches [22] to derive limits on the top-squark for this case. In Fig. 4 we show an exclusion plot in the m_0-$m_{1/2}$ plane. The nearly horizontal dashed lines are chargino mass contours and the lines forming radial patterns are the top-squark mass contours. The upper to the lower radial curves corresponds to $m_{\tilde{t}_1} = 120, 100$ and 80. The region limited by the dotted-dashed line is defined by $m_{\tilde{t}_1} < m_{\tilde{\chi}^+_1}$. The analysis rules out m_0 and $m_{1/2}$ points in the dark hashed region. In the lower hashed region no points with radiative electroweak symmetry breaking can be found. We have taken $\tan\beta = 3$, $A_0 = -650$ GeV and $\epsilon_3/\mu = -0.5$ and verified that in this region $BR(\tilde{t}_1 \to b\tau) = 1$. The Tevatron limits can not be directly applied when $A_0 > -500$ GeV, because in this case $m_{\tilde{t}_1} > m_{\tilde{\chi}^+_1} + m_b$. The regions in the m_0–$m_{1/2}$ plane where $m_{\tilde{t}_1} < m_{\tilde{\chi}^+}$ are excluded if $-650 < A_0 < -500$ GeV and $|\epsilon_3/\mu|$ is sufficiently large so that the three-body decays are negligible. Fig. 4 shows that the region where $m_{\tilde{t}_1} < m_{\tilde{\chi}^+_1} + m_b$ and $BR(\tilde{t}_1 \to \tau^+ + b) \approx 1$ is practically ruled out by experiment. For this particular choice of SUSY parameters there is only a little window still to explore at the run 2 of Tevatron. However for other choices of SUSY parameters, e.g. $A_0 = -900$ GeV the dark-hatched region fills up only about half of the allowed region where $m_{\tilde{t}_1} < m_{\tilde{\chi}^+_1} + m_b$ and would therefore be open for investigation at the next run.

The MSSM three-body channels could be competitive with the BRPV one if $|\epsilon_3/\mu|$ is very small and $m_0 \ll m_{1/2}$. In this case the condition $BR(\tilde{t}_1 \to \tau^+ + b) \approx 1$ no longer holds and our analysis is not applicable. If $|\epsilon_3/\mu| < 10^{-3}$ (which leads to tau neutrino mass in the 10^{-2}eV range in the mSUGRA model) for the same value of $\tan\beta$ we find [23] that the decay mode into $c\,\tilde{\chi}^0_1$ is competitive with the $b\tau$ channel. The $\tilde{t}_1 \to c\tilde{\chi}^0_1$ channel becomes more important for large $\tan\beta$ and $m_{\tilde{t}_1} < m_{\tilde{\chi}^+_1}$. In this case one needs $|\epsilon_3/\mu| > 10^{-2}$ in order to get a negligible $BR(\tilde{t}_1 \to c\tilde{\chi}^0_1)$.

IV SUMMARY

We have studied top-quark and top-squark decays in a supersymmetric model with bilinear R-parity breaking. We have found that in both cases there exist additional top and stop decay modes leading to novel phenomenological implications with respect to those of the MSSM. In the top-quark case the new decay modes are $t \to \tilde{\tau}^+_1\,b$, $t \to \nu_\tau\,\tilde{t}_1$, and $t \to \tau^+\tilde{b}_1$. We have shown that existing data on non-W top decay from Tevatron are already sensitive to the BRPV parameters, adding both sbottom and stau decay channels.

In this model the top-squark has the additional channel $\tilde{t}_1 \to \tau^+ + b$. This channel will be 100% if the stop is the lightest SUSY particle, which is possible in the BRPV model. Moreover, we have demonstrated that this decay can be dominant even when the lightest neutralino below the stop and the R-parity breaking parameters $|\epsilon_3|$ and $|v_3|$ are well below a GeV, as long as the R-parity conserving chargino decay mode is kinematically closed, i.e. for $m_{\tilde{t}_1} < m_{\tilde{\chi}^+_1} + m_b$. We have studied scenarios in a SUGRA model with universality of the soft breaking terms at the unification scale and we have found that the Tevatron data on third generation lepto-quark data rule out scalar-top masses below 80-100 GeV, depending on the parameters. Additional analysis to determine the sensitivity region for this is now underway [24].

ACKNOWLEDGEMENTS

This work was supported by DGICYT under grant PB95-1077 and Acción Integrada Hispano-Austriaca HU1997-0046, by the TMR network grant ERBFMRX-CT96-0090 of the European Union, by CNPq and FAPESP (Brazil), by Programa de Apoio a Núcleos de Excelência (PRONEX), by a CSIC-CNPq exchange agreement. D. A. R. was supported by Colombian COLCIENCIAS fellowship. W. P. was supported by the "Fonds zu Förderung der wissenschaftlichen Forschung" of Austria, project No. P13139-PHY. L. N. was supported by Spanish CSIC fellowship.

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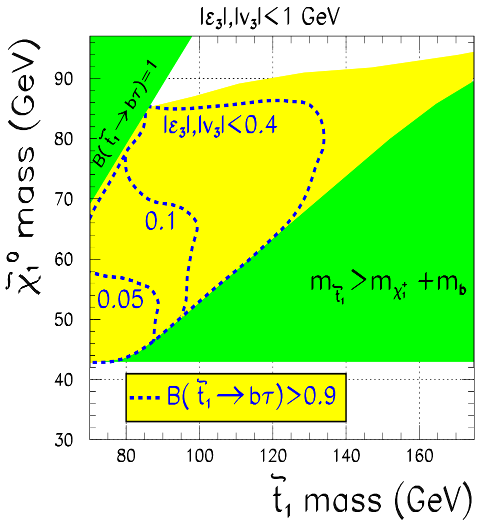

Fig. 3: Contour-lines for BR($\tilde{t}_1 \to b\tau$) > 0.9 in the $m_{\tilde{t}_1}$–$m_{\tilde{\chi}^0_1}$ plane. The gray region shows the area where only those two decay modes are open. We consider $|\epsilon_3|, |v_3| < 1$ GeV, and the MSSM parameters are varied randomly such that $m_{\tilde{t}_1} < m_{\tilde{\chi}^\pm_1} + m_b$. The lines are defined by the maximum value of $|\epsilon_3|$ and $|v_3|$ and delimit the regions where $BR(\tilde{t}_1 \to b\tau) > 0.9$.

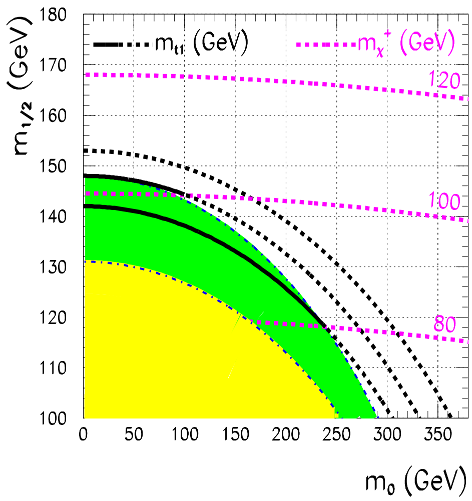

Fig. 4: Exclusion contour in the m_0–$m_{1/2}$ plane. The nearly horizontal dashed lines are chargino mass contours while the radial-like dashed lines are the top-squark mass contours. These change from solid to dashed when the top–squark becomes heavier than the lightest chargino. The radial curves correspond to $m_{\tilde{t}_1} = 120, 100$ and 80, respectively, from upper to the lower. The region limited by the dotted-dashed line has $m_{\tilde{t}_1} < m_{\tilde{\chi}^+}$. The dark hashed region is excluded by experimental data while the lower light-hashed region is disfavoured by theory. We have fixed $\tan\beta = 3$, $A_0 = -650$ GeV and $\epsilon_3/\mu = -0.5$.